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ILLUMINATING ENGINEERING SOCIETY

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VOLUME XVII
No. 2 — 1952

32 VICTORIA ST
LONDON, SW1

Annual Subscription to Non-Members - £2.2.0
Price per Number to Non-Members - 5s. 0d.

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Research, Technological Progress and Illumination*

By L. J. DAVIES, M.A., B.Sc., A.M.I.E.E. *(Fellow)*

One is accustomed to hearing illumination spoken of as a science and an art, and not usually as one of the technologies. A brief definition of a technology is " the science of an industrial art."

A special matter of great concern these days is the need for technological progress, and the means to secure it. We are told that greater production and productivity, and the rapid translation of new ideas into practice, are essential for our nation's well-being.

Never before has there been so much emphasis placed on the need for technically trained men, for better equipment in our factories, for the expansion of our universities, and for more and more research. I am only repeating what, in recent years, has been said almost *ad nauseam*, and I do not propose to add to the general views. They are not the direct concern of this Society, but progress in the technology of illumination is, and I would like to analyse to some extent this complex subject of technological progress, in the hope that a greater understanding is in itself a contribution.

Let me hasten to say that, because I do this, I do not imply that we are not already well forward in this country in illumination technology. We learn, as we should do, from others, but we also contribute. I need only mention as examples the work on some of the most successful fluorescent powders now in use, the development of very high-power high-brightness lamps, the studies on appraisal and visual performance, and the origination in this country of street lighting by fluorescent lamps, which is beginning to spread into the cities and towns of the world.

Let us look, therefore, at the pattern that secures technological advances. The parts of it are research, development, engineering, production and utilisation. The majority of those who strive to make up the combined effort will not be research workers—they will be engineers, production men, commercial engineers, salesmen and users. It is natural, however, that I should consider closely the part that research has to play. The first point I wish to make is that research should not be isolated, but must be appreciated and utilised to be of value. The responsibility to do this lies on all who work on illumination matters, even though they may not be members of a research laboratory. They should understand its aims and methods, and, I am going to suggest, indulge in a little gentle research themselves.

The word " research " itself is becoming overworked, being used quite frequently and sometimes too glibly. The subject can be broken down into some definable subdivisions, and a useful classification is that suggested by Sir Edward Appleton: Fundamental Research; Objective Fundamental Research; Applied Research.

Fundamental Research is that which adds to the sum total of the world's knowledge, unravelling the secrets of Nature without regard for the consequences. These may be profitable, useful, beneficial, or apparently disastrous, and this depends upon *applied research*, and the way the results of applied research are used.

Objective fundamental research stands between fundamental and applied research. It seeks the uttermost exploration of those subjects which are already being, or likely to be, successfully used in some branch of technology.

Applied Research is that branch of research which seeks to obtain practical benefit from the new discoveries of fundamental research.

These are useful divisions. Sometimes the first class is called pure or academic. A

* This paper is the Presidential Address delivered by Mr. L. J. Davies at a meeting of the Society held at the Royal Society of Arts in London on October 10, 1950, the publication of which has been unavoidably delayed.

great part of applied research can be called development. The actual labels do not matter greatly. Let us illustrate those we have chosen by some examples pertinent to our own field, starting with fundamental research—the field of the elect few.

(1) Fundamental Research

Of the two matters basic to illuminating engineering, the nature of light itself and the methods of generating light, the first is so fundamental to physics, and indeed to the universe, that the illuminating engineer may be forgiven if, with Dr. Johnson, he says, "We all know what light is, but it is not easy to tell *what* it is." While we should have great respect, we need but little practical regard for the majority of the work of those great scientists who have endeavoured to determine what light is by seeing how it *behaves*. For example, it does not matter at all in our everyday work that there has been a controversy on whether light is corpuscular or a wave motion. We need not feel any self-reproach over such things, for fundamental research is, and should be, aloof from practical affairs. Its job is to build an edifice of understanding. Many of the bricks that are laid seem to the practical man, even if he can discern them, of little importance. Even though the scaffolding is never noticed except by the intellectual few, sooner or later the structure becomes clear, firm, and usable. Such, for example, is the Einstein equation which tells us that energy equals mass multiplied by the square of the velocity of light. It tells us that if *all* the energy in a pound of coal could be utilised directly it could supply the total electric lighting load of this country for two years.

Such apparently fanciful statements can only be made because of immense labours of fundamental research workers over very many years—scarcely appreciated while they are going on. However, the evidence from an atomic bomb explosion should be sufficient to convince even the most practical of men that such labours may one day turn a large part of fancy into fact.

Turning to the generation of light, we all want a *new* light source—more efficient, without time delays on starting, requiring no auxiliary gear, good colour and long life. It would seem that here is a subject on which we could expect to find a good deal of fundamental research effort leading to discovery. Yet we find virtually none. Why is this?

It is interesting to note first of all that all existing light sources are based upon four primary processes, all of which have been known for 150 years or more, none of which have been discovered by systematic research.

Combustion and incandescence must have been known from the earliest of times, fluorescence was noted in the Middle Ages, and the outcome of the electric arc was an accidental discovery. But the experimenter who made the discovery, Sir Humphrey Davy, was carrying out fundamental work. He was primarily a chemist who saw, in the recent discovery of the voltaic pile as a source of continuous electric current, a new tool for chemical analysis. He was the first man to isolate sodium and potassium by electrolytic methods. During his experimental work with voltaic piles he discovered that an electric current could be passed between soft charcoal electrodes through air in the form of a brilliant luminous arc.

In the same year, 1802, he gave one of the first demonstrations of electrically produced incandescence. He showed that the current from a voltaic pile, if passed through a platinum wire or a slender carbon rod, caused them to glow until they were consumed by oxidation.

The arc and the incandescent lamp thus had their roots in the scientific experiments of the same man in the same year. Seventy-six years afterwards applied research and engineering gave us the first street-lighting with carbon arcs, and the first practicable incandescent lamps.

Considering the above we can gain a further insight into what fundamental

research means to us. For the applied research people—the men who work in the lamp research laboratories of industrial firms—to make a really new light source requires a fundamental discovery. Such is not likely to be discovered accidentally by an amateur. Davy was not an amateur. Nor indeed is the discovery very likely to be made by a deliberate research—for what man of science would do other than laugh if one said to him "Set to work and find a new and practicable way of converting electrical energy into light." But there is always the chance that a discovery may arise out of the many and varied researches into basic knowledge that are being carried out. So let us leave fundamental research, always having great respect for those men who carry it out, with as many funds as possible, and with the fervent hope that in our effort to gain technological progress no one will attempt to organise our search into the unknown.

(2) Objective Fundamental Research

It is when we turn to objective fundamental research that we can begin to organise for technological progress, for this work is basic enquiry directed to matters that are known to have potential application. An example, the direct impact of which on illuminating engineering can be clearly appreciated, is that of glass, a substance essential to our technology. Without it our light sources would be confined to flames, the open arc and Nernst filaments, projection could only be carried out by mirrors, and fittings would use only plastics. Yet glass has been known since the time of the Egyptians, and the vast majority of our lamp bulbs and illuminating glassware could be made with fair satisfaction with glass of not very different composition from that then used. Yet objective work, a great deal of it in the laboratories of industrial firms, is going on most actively. What does this work seek to do? It endeavours to discover the structure of glasses and to tell us why some oxides form glasses and others do not; it seeks to discover why glass fractures in the way it does, and to explain why glass fibres are stronger than sheet glass, and why glass in various forms has only one-tenth to one-hundredth the theoretical strength it should have. It studies the effect of chemical composition and structure on refractive index, viscosity, dielectric constant, and other properties. As a result of this work we begin to know more and more about glass, and, either as an indirect or a direct result of it, an ever increasing range of glasses emerges from our glass technologists. The examples of objective fundamental research work of interest to the illuminating engineer could be clearly multiplied by including the chemistry of polymers, the physiology of light perception, the physics of single crystals (which may lead to improved magnetic materials and thus lower loss chokes), and other developments.

It is clear that, as members of this Society, we are concerned either remotely or by direct contact with these two great classes of research, and thus draw upon a vast array of scientific effort. This includes work on the physics of light emission and absorption of thermionic emission and of discharges through gases and vapour, on the chemistry of glass, plastics and fluorescent materials, on the metallurgy of tungsten, on electrical, mechanical and gas engineering, on steel and non-ferrous alloys, on concrete, physiology and architecture.

We draw upon these efforts by means of applied research and, backed up by engineering, production, utilisation and service, they are of the greatest importance to technological progress.

(3) Applied Research

It is in applied research that the work comes closer to the illuminating engineer, and quite a number of our members are directly engaged in it. It takes known results and seeks to apply them to achieve a practical objective. From many possible examples I will take that of the fluorescent lamp. By the application of applied research,

virtually a new lamp was created which, in itself, contains nothing that was not already known.

A discharge through mercury vapour at low pressure emits ultra-violet radiation; nature decides this—not man, but the conditions of pressure, current-density and other factors for the maximum conversion of electrical energy into this radiation have had to be worked out. The ultra-violet radiation is converted into visible light by fluorescence. It is nature that is responsible for this transformation, and even provides us, in willemite, with an example to show what is possible, but applied research has had to develop efficient phosphors in a range of colours. It is easy to confine the mercury vapour within a glass tube opaque to ultra-violet radiation but transparent to visible radiation and to coat the inner surface with fluorescent material, but the discharge must spring from electrodes. Applied research tells us that, in order for the lamp to have a voltage drop suitable for ordinary mains voltages and a reasonable length and efficiency, these electrodes must give up the electrons required for the discharge easily and copiously. It uses a discovery made by Wehnelt in 1904, that electrodes coated with an alkaline earth metal are good electron emitters. But something more is required, for the lamp not only has to run but to start on ordinary mains voltages. This requires that the electrodes must be emitting a copious supply of electrons, and therefore must be hot at the moment of starting. In order for the lamp to be practicable, the electrodes must be rendered hot with the minimum of auxiliary switchgear, and so the applied research that has produced bimetal, a material which alters its shape with temperature, is called in. This material enables a simple switch to be developed that will cause a delay while the cathodes are warmed, apply the mains voltage, and then isolate the cathode heating current. Finally, since the lamp has a negative characteristic, the electrical engineer is called upon to design and produce a reactance or choke of small size and low loss.

All these items, glass, fluorescent powder, discharge through mercury vapour, coated cathodes, bimetal and reactance were separately known before an efficient mains voltage lamp was made, but it required invention to combine them, and applied research to work out the principles of design so that development of a high efficiency and practicable production article was possible.

(4) Engineering, Production, Installation and Service

After applied research has shown whether or no an objective can be reached, the extent to which success will be achieved depends upon the judgment and energy of those who, in fact, make up the majority of the membership of this Society. It is the manufacturers of lamps and equipment, the design and application engineers, the specialists in the various forms of lighting, and the commercial engineers who, with the users, eventually bring into actual being a new or improved lamp, fitting, or installation

Already this judgment and energy should have played its part in initiating the applied research, for this effort gains impetus because of two pressures—one from within derived from the eagerness of the applied research worker to seize upon every new development to turn it into something of use, and one from without, from the engineers and users demanding practical embodiments of those new developments which their experience tells them may be worth while.

Let me recapitulate, at this stage, regarding the position of research and the members of this Society. The fundamental research worker, the gainer of new knowledge, stands aloof or should do. But his work is of no avail unless it is in due course utilised wherever possible. To do this requires inter-related teams or groups, the objective research men, the applied research people, the engineers, manufacturers, specialists and commercial engineers. All have a part to play if new developments are to be born and used—and especially important is the part to be played by the groups

who would not perhaps consider that they have any responsibilities in connection with research. They have definite responsibilities, however, because technological progress requires that research be used.

I will now go further and suggest that, in all our work, whatever it may be, there is an opportunity to do research by using some part of our environment as a research laboratory, and if we can gain some experience and insight by doing this we are more likely to use the research of others.

There are, firstly, a number of obvious items, attention to which by way of keeping careful records will provide data. Take, for example, the life of lamps. The maker of lamps does extensive life testing in the laboratory, but two factors intervene to prevent the final picture obtained being as complete as it should be. There are never enough life test sockets, and the ultimate measure of quality is the behaviour, not only under laboratory conditions, but in the field. Some users are extremely co-operative and provide valuable data which is gratefully accepted. But if more users, instead of writing the congratulatory letter which all lamp makers hope one day to receive on the Methuselah-like life of his lamps, or the more usual complaint, could say "Here is a record giving the approximate life hours and conditions of use of some of your lamps," such items of data fed into an applied research laboratory from here and there one day will make a complete picture which may contain valuable data. For example, if a lighting engineer can show that, in an installation under his care, lamps are not behaving properly, and if all other field evidence contradicts this, then clearly there is a harmful factor specific to this installation. This can then be investigated by a co-operative effort of the research men and the lighting engineer in the field, isolated, and either removed or the breed of lamps improved to meet the condition. Without the co-operation of all those who supplied the data, this factor may have been overlooked and a useful development in quality may have been delayed.

A most important research avenue is the assessment of the tangible benefits of improved lighting. We are all convinced of these benefits. We are quite sure that if one takes a poorly lighted production area and installs in it an up-to-date lighting installation, raising the illumination from, say, 5 lm./ft.^{2} to 25 lm./ft.^{2}, reducing the glare, providing light on danger spots where before it was absent, it is worth while. But to do this costs quite a lot of money. The transformed look of the work area is to the lighting engineers who plan the job, and to wise management which secured the capital appropriation, sufficient reward, but if statistics could be collected, how valuable ultimately the volume including them would be!

This is field work, and the research outlook is necessary. Sometimes installation of new lighting coincides with a rearrangement of the work area or the tooling up for new production, and due to several factors being changed at once, definite conclusions are not possible. At other times the only significant change is in the lighting installation. Then, if the lighting engineer can secure the co-operation of the factory superintendent, the following records may be compiled before and after the change—Productivity; Accident Rate; Absenteeism Rate; Labour Turnover Rate.

One must not expect clear-cut results, for some of this data is difficult, but if a number of records could be collected and examined statistically it may be shown, for example, that whenever a new lighting system is installed there is a slight improvement in one or all of the above items—and if the economical factors are then written into the account, I am sure that even a slight improvement, for example, in labour turnover, which is a most expensive item in a factory, would go a long way in justifying the overall costs of the new equipment.

In this connection it would be of interest to consider, when the main installation of lighting has been planned, the value of what may be termed "worker amenity" lighting.

Special lighting for notice-boards, or near a drinking fountain, or in a cloak-room,

or for flood-lighting the achievement boards, would add but comparatively little to the capital cost or the running cost, and yet might be just one of those things that would make the worker more pleased with his environment—and this in itself is an important factor in technological progress.

Again, there are many opportunities for experiment in one's personal lighting, and experiments here will get one out of the habit of accepting too credulously the recommendations of others. For example, it used to be considered a good thing for concentrated mental work, to throw a bright pool of light on one's papers from, say, a desk light with an almost opaque top, and to switch off the room lights and thus cut out all distraction. Nowadays we know that the workpiece—in this instance one's papers—should only be just brighter than its surroundings, and I am sure that this is right. But am I sure? I am not so sure after reading Mr. Waldram's Presidential Address of 1948; but the point is—have I ever tried it for myself?

I spend a lot of time at a desk, the top of which is light brown oak. Would I feel better, more comfortable, work more efficiently if the top was white or light green? It would be but a trivial expense for me to obtain the necessary sheets of paper that would enable me to make the trial. The only thing I must remember to do is to keep the experimental conditions under control. To work for, say, one hour a day for several days, alternately under the respective test conditions, always for the same hour of the day, and as closely as possible on similar tasks, and then to introduce a quantitative visual test task, e.g., Landolt's broken rings. If I carried on the test long enough, and if I always found that I obtained more errors with a dark top desk as compared with a light one, I should have added something new to my knowledge.

A good opportunity for home research work concerns the best system of room illumination for television viewing. With the increase in number of aluminised screens of high luminance, the contrasts on the screen can be great, as also can be the contrast of the screen with its immediate surroundings and the remainder of the room, since we must avoid reflections of light sources or illuminated areas in the screen itself. My experiments are leading me in the direction of viewing the screen through a hole cut in a sheet which can be illuminated from behind, or to painting the television cabinet white—neither very acceptable domestically, but to solve all kinds of problems, not only the technical ones, when doing research at home is part of the general interest.

But the best research is done, not when the problem is suggested, but when it occurs in one's mind, when one is struck by an inconsistency, when one asks "Why?" I do not want to appear unappreciative of the fact that good research work takes time and patience, and I know that if one is a designer of fittings, a research physicist on lamps, a street lighting engineer, one has one's own job to do. Nevertheless I make the appeal to our members not only to take note of the work of others to see if it can be applied, but also to keep a sceptical mind and not to be afraid of undertaking a little gentle research on their own.

Conclusion

I have endeavoured to indicate that research fits into a pattern in which the various types of research merge progressively with engineering, manufacture, installation and distribution, but that it can only be fully effective if members of all groups give it proper regard. I have then ventured to suggest that there are plenty of opportunities in illuminating engineering for any one of us to indulge sufficiently in investigation to become truly research minded, and if we do we shall help the technological progress of illumination, which is no new objective of this Society, for "to promote the advancement of illuminating engineering" was one of its first objects when the Society was founded 41 years ago.

The Measurement of Sector Flux

By H. D. EINHORN, Dr. Ing., Ph.D., *(Member)*, and
K. R. ACKERMAN, B.Sc.[Eng.], *(Member)*.

Summary

"Sector Flux" is a new concept proposed for the theoretical treatment of long linear sources, such as fluorescent lamps mounted end to end. Its measurement is discussed and a method employing parallel mirrors is described.

This treatment permits prediction of the light distribution from linear installations, based on measurements made on a single fitting in the laboratory.

List of Symbols

J = Sector flux (in lumens/ft./radian).
R = Radial distance from source (in ft.).
E = Illumination (in lumens/sq. ft.).
C = Centre distance between fittings of an installation,
= Distance between mirrors (in ft.).
L = Effective lamp length (in ft.) = $0.92\times$ luminous length of bare fluorescent lamp.
G = $C-L$ = Gap between lamps including allowance for dark end effect (in ft.).
ρ = Reflection factor of mirrors.
τ = Transmission factor of glass plates.

(1) Introduction

Linear arrangements of light sources are used frequently in modern installations, particularly in the form of end-to-end mounting of fluorescent lamps.

Predicting or analysing the performance of such installations, based on the calculation of illumination values, is facilitated if the concept of "Sector Flux"[1] is introduced.

In accordance with the inverse-first-power law which applies to long linear sources, the illumination at a point P on a plane parallel to the source is

$$E = \frac{J}{R}\cos\theta$$

where J is the sector flux, θ the angle between the normal to the illuminated plane and the line connecting P to the nearest point of the source, and R the distance from P to this nearest point.

"Sector Flux" is related to a linear source in a similar way as "Intensity" is to a point source, indicating the amount of light sent out in a particular direction. It can be used as vector in a polar curve.

"Sector Flux" is defined as "Flux per unit length per unit angle" and is measured in lumens per foot per radian (or, lumens per metre per radian).

It is the object of this paper to discuss convenient methods of measuring this new quantity.

(2) Measurement of Sector Flux on Complete Installation

If it is practicable to mount a sufficient number of lamps in a laboratory with dark ceiling and walls, the measurement of sector flux is easily made. A single illumination reading E on a cosine-corrected photovoltaic cell placed at a distance

Dr. Einhorn is at the University of Cape Town, Union of South Africa, and Mr. Ackerman is with the British Thomson-Houston Co., Ltd., Rugby. Manuscript received April 5, 1951.

R from the lamp and facing it should be sufficient to determine the sector flux J, as $J = ER$.

If the measurement is to be made *in situ*, reflection from light walls and ceiling has to be eliminated by careful screening of the photocell, the screens being arranged parallel to the light source.

(3) Measurement of Sector Flux on Single Fitting

It is often more useful to predict the behaviour of an installation from laboratory measurements on a single fitting of the type to be used.

For this purpose a simple arrangement of two parallel mirrors (M) is proposed, between which a fluorescent lamp and a cosine-corrected photocell (P) are placed as shown in the inset of Fig. 3.

The lamp itself and its successive images in the mirrors present to the photocell the appearance of an infinite linear source. The reading E of the cell, multiplied by the distance R should, therefore, give the sector flux J of the lamp in the direction of the cell. The distance C between the mirrors must be equal to the distance between the centres of adjacent fittings in the proposed installation.

Turning the lamp or, alternatively, swinging the mirrors and photocell round the lamp axis, would permit the measurement of a polar curve (in units of lumens per foot per radian).

The total flux of the fitting tested can be obtained from a set of n sector flux readings taken at equal angular intervals,[1] as

$$F = 2\pi C \frac{1}{n} \Sigma J_n \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

(4) Sources of Error in Measurement on Single Fitting

The following experimental difficulties and possible sources of error were investigated:

(a) Misalignment of mirrors;
(b) Absorption of light by mirrors;
(c) Light variation along the axis of the infinite source due to end-darkening of lamps and to gaps between them.

The mirror should be aligned at right angles to the axis of the fluorescent lamp. It was found that visual alignment is very easy, since measurable errors only occur when the row of lamps seen in the mirrors appears noticeably bent or uneven. It is, however, advisable to check whether the mirrors are parallel.

Absorption of light by the mirrors is serious and necessitates the use of a correction factor. This effect increases with the distance (R) of the photocell from the lamp and apart from economic considerations makes the choice of a moderate distance R desirable.

The effect of light variation along the source axis as caused by end-darkening and gaps between lamps, on the other hand, decreases with distance R.

These two effects limit therefore the useful range of R. They will be discussed in detail in the following section, prior to a final recommendation for the determination of J.

(4.1) Correction for Mirror Absorption

The effect of mirror absorption varies with the reflection factor ρ of the mirrors and the emission characteristics of the light source. It can be calculated for defined emission types as shown in Appendix 1.

Figs. 1 and 2 show the correction factor e, a dimensionless ratio equal to ER/J,

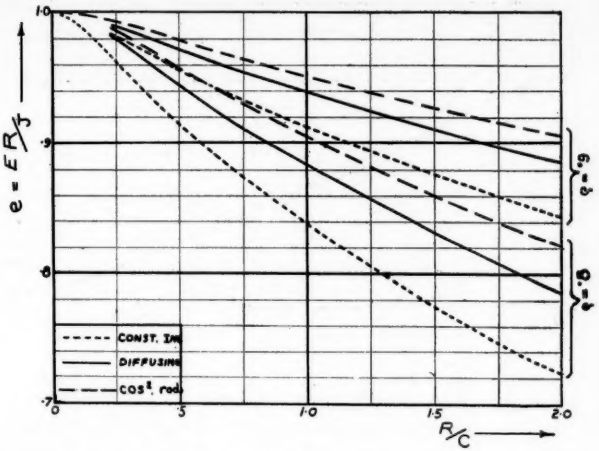

Fig. 1. Correction factors for mirror reflection, calculated for cosine squared, diffusing and constant intensity.

as a function of the relative distance R/C with the photocell positioned at $0.25C$ from one of the mirrors (see inset Figs. 3 to 6).

Fig. 1 gives correction curves for a cosine squared radiator, a cosine radiator (diffusing source) and a constant intensity radiator (such as a row of uniform point sources).[1] Two sets of curves for $\rho = 0.9$ and $\rho = 0.8$ are shown. For any type of source, $e = 1.0$ for $\rho = 1.0$.

Fig. 2 gives curves for fluorescent lamps, which are considered as being midway between cosine and cosine squared radiators.

(4.2) Light Variation Along Axis of Source

The variation of light emission along the source axis due to gaps, etc., causes a variation of the illumination E measured at constant distance R, when moving the photocell along a line parallel to the source.

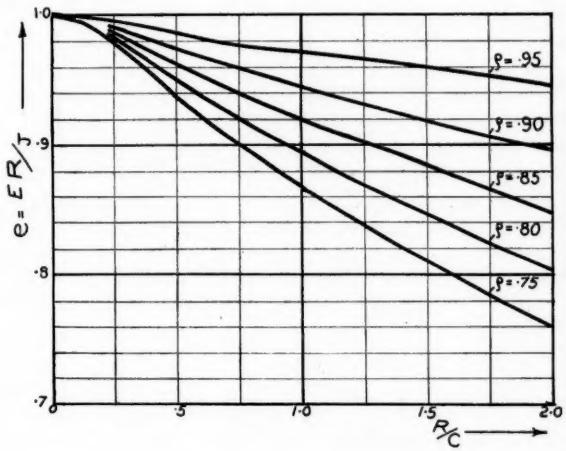

Fig. 2. Correction factors for mirror reflection, calculated for fluorescent lamps (mean of cosine and cosine squared radiators).

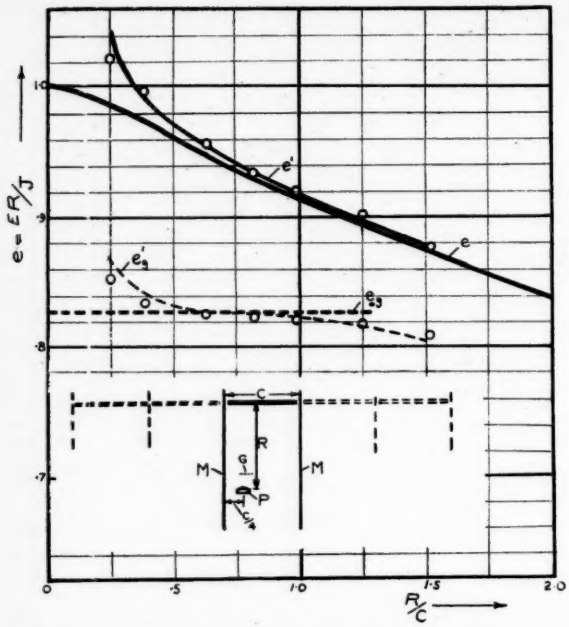

Fig. 3. Calculated curves for mean cosine and cosine squared radiators, and experimental points for bare 30-watt fluorescent lamps mounted end to end.

In determining the sector flux as the product ER, the correct value E can be defined as the average of all values of E, measured at constant distance R.

The values measured below the centre of a lamp are usually higher, and those below the centre of a gap usually lower than this average value. It was found from preliminary tests on different fluorescent lamp fittings that the illumination measured midway between these extreme positions differs by less than 1 per cent. from the average value when R/C is greater than 0.75. It is therefore recommended that measurements should be made with the photocell at a distance of $0.25C$ from the mirror, corresponding to this midway position, and at a distance R greater than $0.75C$ from the lamp.

To allow for any asymmetry of the lamp or fitting two readings are as a rule required, one on each side of the mid point.

(5) Proposed Determination of J

(5.1) Normal Method

The Sector Flux can be rapidly and simply obtained as follows:

Two illumination readings E_1 and E_2 are taken at quarter distance, $0.25C$, axially from either mirror and at radial distances R_1 and R_2; R_1 should be approximately equal to R_2 and neither should be less than $0.75C$.

The Sector Flux is then obtained from the mean product as

$$J = \frac{E_1R_1 + E_2R_2}{2e} \qquad \text{.....(2)}$$

The correction factor e is to be taken from Fig. 2 for bare lamps or lamps in plain reflectors, while the cosine-squared radiator curves of Fig. 1 serve as approximation for louvred lamps.

(5.2) Modified Method: Insertion of Glass Plates

To reduce the variation of the *e*-ratio with distance and thereby eliminate the necessity for using the correction curves of Fig. 1 or 2, a glass plate can be inserted above the photocell, so as to be in the path of direct light from the lamp without appreciably interfering with light from the mirrors, as shown dotted in the insets of Figs. 3–5. Thus by inserting a glass plate whose transmission factor τ equals the reflection factor ρ of the mirrors, light from the first three sections of the infinite source, $3C$ long, is reduced by a constant factor ρ, and only those relatively distant sections of the source which are produced by *multiple* reflection show a further reduction of brightness.

One can further reason that by selecting glass plates of slightly higher absorption than that of the mirrors the product ER can be made approximately constant over a fair range of R/C, thus allowing the use of a constant correction factor e_g.

From theoretical reasoning and experiments an empirical value was found, namely:

$$e_g = \frac{2}{3}\tau + \frac{1}{3}\rho \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

giving a reasonable approximation over the range $0.75 < R/C < 1.25$, if for fluorescent lamps $0.85 < \tau/\rho < 1$, while for point sources $0.75 < \tau/\rho < 0.90$.

(6) Experimental Verification

Tests were carried out to check whether illumination readings at different distances varied in accordance with calculated values.

Two ordinary commercial mirrors of 84 per cent. reflection factor, each 5 ft.

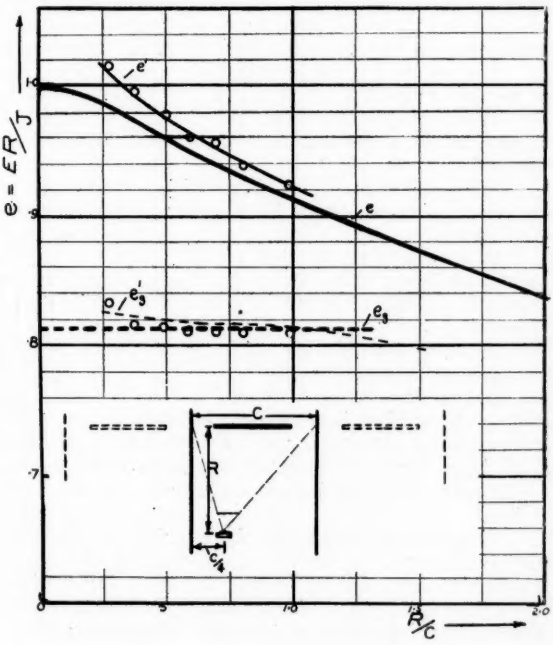

Fig. 4. Calculated curves for mean cosine and cosine squared radiators and experimental points for bare 30-watt fluorescent lamps spaced at a distance.

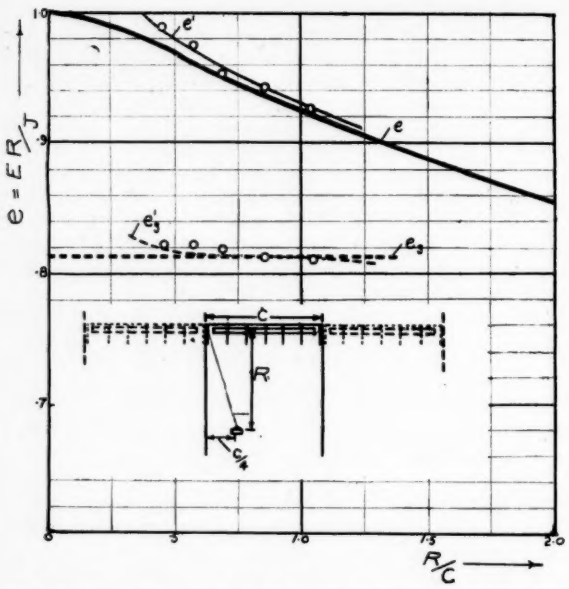

Fig. 5. Calculated curve for a cosine squared radiator and experimental points for a louvred 40-watt fluorescent lamp.

by 8 in., were mounted on a wooden structure which allowed adjustment of distances up to 5 ft. For the modified method, two glass plates of different thickness were placed together to obtain the desired average transmission.

The results were plotted in the form of ratios ER/J (permitting large ordinate scales for critical inspection) for the following four arrangements of sources :—

(i) Bare fluorescent lamps, end-to-end (Fig. 3); (ii) Bare fluorescent lamps, spaced (Fig 4); (iii) Louvred fluorescent lamps (Fig. 5), and (iv) A row of incandescent lamps (Fig. 6).

The latter forms a line source of the constant intensity type(1), and this test was included to show that the method proposed is valid for sources of widely different light distributions.

In all graphs the full curve e is the ER/J ratio calculated for $\rho = 0.84$; e' is the curve corrected for the dark-end and gap effect (see Appendix 2); e'_g is the corrected curve for the set up including glass plates, and the straight line is drawn at a level $e_g = \frac{2}{3}\tau + \frac{1}{3}\rho$.

It can be seen that the measured points follow the calculated curves well within the accuracy of measurement.

One measured point, however, had to be fitted arbitrarily, since the actual sector flux of the lamp was not known beforehand. A check on this fit was obtained by measuring the intensity I_L of the lamp and comparing the ratio J/I (where $I = I_L/C$ is the intensity per unit length of installation), with its theoretically expected value (1).

The result of this comparison, carried out for a distance $R/C = 1$, is shown in Table 1.

Very good agreement was obtained for bare fluorescent lamps at both spacings and also for the row of point sources, whereas the ratio for louvred lamps disagreed appreciably from that of a simple cosine-squared radiator. Theoretical considerations show, however, that the computation of J using the correction factor e for cosine-squared radiators will not introduce errors exceeding 2 per cent. in louvred lamps

Table 1.

Source arrangement	Ratio J/I		Type of source
	Measured	Theoretical	
Bare fluorescent lamps, closely spaced	1.47	1.47	Mixture of cosine and cosine-squared radiator ($b=0.42$)[2]
Bare fluorescent lamps, widely spaced	1.48	1.47	
Louvred fluorescent lamps	1.22	1.33	Cosine-squared radiator
Point Sources	1.97	2.00	Constant intensity radiator

similar to the type tested (cut-off angle 36 deg.), while for the more usual cut-off angles of 20 deg. to 30 deg., still better agreement should be expected.

A further check consists in comparing the sector fluxes of closely and widely spaced lamps which should be in the inverse ratio of the distances between mirrors. This checked to within 1 per cent.

For the modified method (dotted curves) the experimental points were not fitted arbitrarily but were drawn in the correct ratio to the points without the glass plates. This forms a final check on the relative levels of experimental points and calculated curves.

(7) Accuracy of Method

Judging by the various check calculations and tests the claim seems justified that the approximations inherent in this method will not lead to errors greater than 1 per

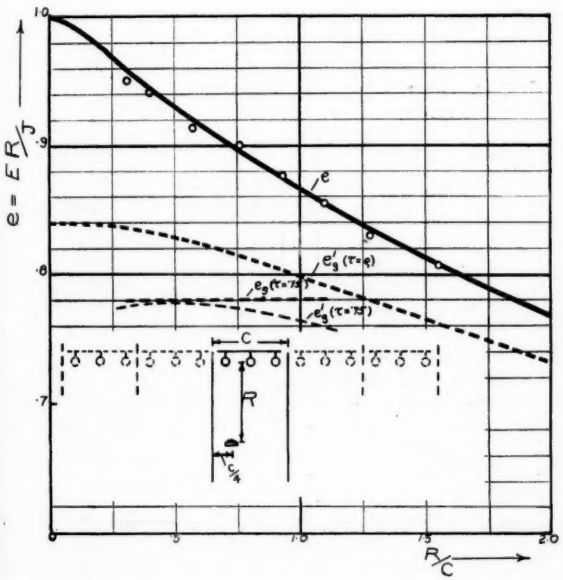

Fig. 6. Calculated curve for a constant intensity source and experimental points for three 40-watt pearl incandescent lamps at 1 ft. centres.

cent. for plain fluorescent lamps, and not greater than 2 per cent. for most types of louvred lamps. These errors are probably smaller than other photometric errors.

The accuracy could further be improved by the following means:—

(i) Employing highly reflecting mirrors (those used in the test were fairly cheap commercial mirrors) to reduce possible errors due to the use of approximate curves for the *e*-ratio. Keeping the measuring distance R below say 1.5 C is recommended for the same reason.

(ii) Since the error due to light variation along the axis of the source is usually positive when measuring below a lamp and decreases with distance R as seen from Figs. 3-5, an empirical correction to equation (2) can be introduced, if desired. Multiplying the sector flux value obtained in equation (2) by a factor $(1\text{-}0.005\ C/R)$ is recommended for all arrangements where the luminous length of lamps exceeds the gap between lamps (see Appendix 2).

As to the modified method employing glass plates, an accuracy better than 3 per cent. should not as a rule be expected, since errors due to misalignment of plates, finger-marks or dust, and inability to procure plates of the most desirable transmission, have to be considered in addition to the empirical nature of equation (3). The dark-end effect is already allowed for in equation (3).

A check on the accuracy obtained with other fittings is always possible by taking readings at different distances and comparing measurements with and without glass plates. If a complete polar curve is taken, the total flux of the fitting can be computed (see equation 1) and compared with the flux measured in an integrating sphere.

(8) Conclusions

The method proposed for measuring the sector flux of an installation of lamp fittings arranged linearly, using only a single fitting, is simple, being based on two illumination readings only.

Unless rotation of mirrors is desired the equipment needed is not very expensive and space requirements are moderate.

Since the spacing of the mirrors corresponds to that of lamps in the prospective installation, a maximum spacing of seven to ten feet should be adequate for most practical purposes, with a mirror length of some five to seven feet.

The width of the mirrors required depends on the width of reflectors to be tested.

Published polar curves of commercial fluorescent lamp fittings in terms of sector flux would form a useful aid for handling a number of lighting design problems.[1]

The method described in this paper offers a convenient means for obtaining the necessary data in the laboratory.

Acknowledgment

The authors' thanks are due to the Fourcade Research Fund of the University of Cape Town for financial assistance towards the purchase of equipment.

References

(1) Einhorn, H. D., Trans. Illum. Eng. Soc. (London), **16,** 101 (1951).
(2) Einhorn, H. D., and Sauermann, J. D., Journ. Inst. Elec. Eng., **94,** Part II, 535 (1947).

Appendix 1

Calculation of Correction Curves for Mirror Absorption

Consider a tubular lamp having uniform light emission along its axis and placed between two mirrors spaced at C feet. A cosine-corrected photocell P placed R feet from the source, will "see" the real lamp and a series of images produced by the

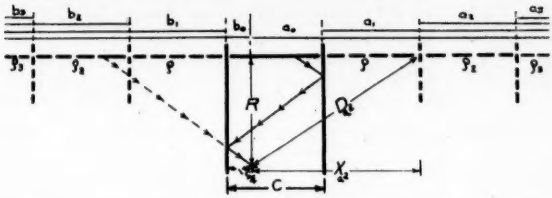

Fig. 7. Mirror-produced infinite source, considered as superimposed set of semi-infinite sources.

parallel mirrors by single, double, triple, etc., reflection (Fig. 7). The images are progressively dimmer, their luminances being multiplied by factors ρ, ρ^2, ρ^3..., where ρ is the reflection factor of the mirrors. The illumination at P can be calculated as the sum of the illumination values produced by the individual images.

In order to make use of previously calculated results from semi-infinite sources(1), let us introduce illumination values produced by semi-infinite sources a_0, a_1, a_2 ... and b_0, b_1, b_2 . . . . . ending at the respective image boundaries, and let these illumination values be denoted by E_{a0}, E_{a1}, E_{a2}, E_{a3} . . ., E_{b0}, E_{b1} . . . ; (these values are at present defined without regard to absorption).

The true illumination at P is then

$$E = (E_{a0} - E_{a1}) + \rho\,(E_{a1} - E_{a2}) + \rho^2\,(E_{a2} - E_{a3}) + \ldots + (E_{b0} - E_{b1}) + \rho\,(E_{b1} - E_{b2}) + \rho^2\,(E_{b2} - E_{b3}) + \ldots \quad \ldots\ldots\ldots(1.1)$$

For a lamp of axially symmetrical light emission

$$E_{a0} = E_{b0} = \frac{J}{2R} \quad \ldots\ldots\ldots(1.2)$$

i.e., half the value for an infinite source, while the values E_{a1}, E_{a2}, E_{b1}, E_{b2} ... depend on the relative distance R/C and the radiation properties of the source.

The most convenient and sufficiently accurate assumption for a fluorescent lamp is to consider it as the superposition of a cosine radiator (perfectly diffusing source) and a cosine-squared radiator (2). For semi-infinite sources of this type the illumination on a plane parallel to the source is

$$E_{cos} = \frac{J}{R}\left(\frac{1}{2} + \frac{1}{\pi}\tan^{-1}\frac{X}{R} + \frac{1}{\pi}\frac{XR}{D^2}\right) \quad \ldots\ldots\ldots(1.3)$$

and

$$E_{cos^2} = \frac{J}{R}\left(\frac{1}{2} + \frac{3}{4}\frac{X}{D} - \frac{1}{4}\frac{X^3}{D^3}\right) \quad \ldots\ldots\ldots(1.4)$$

where $D^2 = X^2 + R^2$. (For proof see Ref. 1.)

Fig. 8 shows curves of E_{cos} and E_{cos^2} as functions of R/X and X/R; the mean

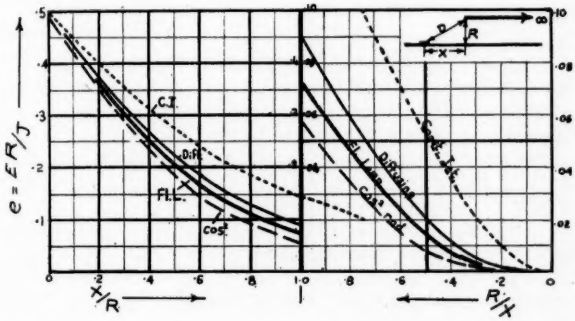

Fig. 8. Illumination beyond the end of a semi-infinite source, on a plane parallel to the source.

of these two curves is applicable to bare fluorescent lamps. The dotted curve represents a line source of constant intensity for which

$$E_{const} = \frac{J}{R}\left(\frac{1}{2} + \frac{1}{2}\frac{X}{D}\right) \qquad \text{.....(1.5)}$$

Equation (1.1) can be simplified making use of equation (1.2) as follows:

$$E = \frac{J}{R} - (1 - \rho)\,[\,(E_{a1} + E_{b1}) + \rho\,(E_{a2} + E_{b2}) + \ldots\, \rho^{n-1}\,(E_{an} + E_{bn}) + \ldots\,] \qquad \text{.....(1.6)}$$

or

$$e = \frac{ER}{J} = 1 - (1 - \rho)\sum_{n=1}^{n=\infty} \rho^{n-1}\,(E_{an} + E_{bn})\,R/J \qquad \text{.....(1.6a)}$$

Equation (1.6) and Fig. 8 were used to calculate the curves in Figs. 1 and 2 and curve *e* in Figs. 3 to 6.

The use of this method can be illustrated by a typical calculation. Take the point $R/C = 0.75$ in Fig. 3, for $\rho = 0.84$.

n	a or b	X/C	R/X	X/R	E_nR/J*	ρ^{n-1}	$\rho^{n-1}\,(E_{an} + E_{bn})\,R/J$
1	b	.25		0.333	0.288		
	a	.75		1.0	0.075		
	a + b				0.363	1	0.363
2	b	1.25	0.60		0.023		
	a	1.75	0.43		0.009		
	a + b				0.032	.84	0.027
3	b	2.25	0.33		0.004		
	a	2.75	0.27		0.003		
	a + b				0.007	.71	0.005
							0.395

(* From the thick curve of Fig. 8 for a mixed cosine and cosine^2 radiator.)
Adding 0.005 to 0.395 (to allow for further terms of $n > 4$), we obtain
$e = ER/J = 1—(1—0.84) \times 0.400 = 0.936$.

Appendix 2

Correction for Gaps Between Lamps

If lamps are mounted with gaps between their ends, the linear source obtained has alternate bright and dark sections. But even if lamps are mounted closely end to end, a dark-end effect occurs due to space requirement for the lamp holders and to the reduced brightness at the ends of fluorescent lamps.

At great distances from the source the illumination obtained is only a function of the *average* light emission J along the lamp and the effect of this periodic variation of light emission becomes negligible.

To establish this effect in the region of measurements considered in this paper, the following estimate is made.

The infinite source is considered as a succession of sections of constant light emission each having an effective length L equal to 0.92 times the luminous length

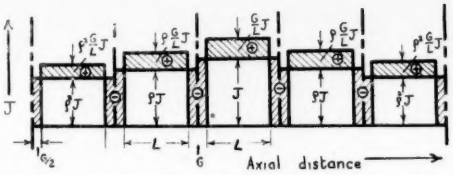

Fig. 9. Sector-flux variation along mirror-produced linear source allowing for gaps between lamps.

of one lamp (see Ref. 2, sec. 11.4.2), and of dark sections equal to $G = (C - L)$, where C is the distance between the centres of adjacent lamps, and G is the effective gap length. Let us imagine this "periodic" source as the superposition of a continuous source emitting a sector flux J and an alternating source containing sections of positive light emission JG/L over a length L, and sections of negative light emission $(-J)$ over a length G. The reduction due to mirror absorption is also taken into account as shown in Fig. 9.

The illumination obtained from the alternating component (shown shaded in Fig. 9) will give the correction for the dark-end effect. It will usually be positive underneath a lamp, negative underneath a gap, and is most conveniently expressed as a fraction of the illumination produced by the continuous component J.

The calculation is similar to that shown in Appendix 1 making use of Fig. 8. The result is shown by the thin curves e' in Figs. 3 to 6.

Their deviation from the thick curves is a measure of the dark-end effect. It can be seen that for a photocell positioned at $0.25C$ from the mirror, i.e., midway between lamp centre and gap centre, this deviation is less than 1 per cent. as long as $R/C > 0.5$ for closely spaced lamps, while for wider spacing this 1 per cent. limit is reached at a distance R/C equal approximately to 0.75. The correction recommended in Sec. 7 (ii) is based on this deviation.

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